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A systematic literature review on indicators to assess local sustainability of forest energy production

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ABSTRACT

Bioenergy production is considered the single most significant contributor to the climate change mitigation within the forest sector. In addition, the production of forest-based bioenergy may also positively affect social welfare, local development and forest economy. In environmental markets the role of forests and the challenge of combining international, national and local needs related to their sustainable use for bioenergy and social livelihood is increasing. These global ecological and socio-economic changes pose new challenges for ecologically, economically, socially and culturally sustainable utilization of forest resources. The purpose of this literature review is to map the existing indicator sets introduced in scientific literature suitable for evaluating the sustainability of forest-based bioenergy production systems from a local perspective. In addition, also the challenges in assessing ecological, economic, social and cultural sustainability by using different types of indicators are discussed. According to the results of this study, there are plenty of indicators suitable for assessing either the ecological, economic, social and cultural sustainability of forest-based bioenergy production at a local level. In contrast, information on appropriate procedures for taking into account local development goals abreast with the objectives of sustainable development at general global level are lacking. Additionally, in order to analyze trade-offs in different sustainability dimensions caused by optional decisions regarding forest-based energy production, methodological development would be required. The comprehensive indicators lists presented in this study can employed as background information to define the measures that are especially relevant in enhancing the local sustainability goals from the perspective of different stakeholders in specific localities.

Contents

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1. Introduction

Bioenergy production is considered the single most significant contributor to the climate change mitigation within the forest sector [1]. In addition, utilization of forest resources for bioenergy production may positively affect social welfare, local development and forest economy especially in rural areas [2]. Combining international, national and local needs related to the sustainable use of forests for bioenergy production [3] and supporting social wellbeing, for example, are expected to be major themes in environmental markets in the future [4]. These global ecological, socio-economic and cultural changes [4,6] also pose new challenges and conflicts of interests for ecologically, economically, socially and culturally (i.e., multi-dimensionally) sustainable utilization of forest resources both at national and global level [7].

International bioenergy trade is growing rapidly due to policy incentives (e.g., linked to climate change mitigation), large resource potentials, relatively low production costs, and objectives aiming at increasing the stability of national and regional fuel markets by reducing the dependency on crude oil imports [8,9]. Industrial forest-based bioenergy products comprise different types of biofuels (processed in biorefineries), heat and electricity (produced in combined heat and power, CHP plants), heat (produced in district heating plants), and pellets (manufactured in pellet factories). The characteristics of forest-based bioenergy products, for example, vary considerably depending on the infrastructure needed in processing, the scale of operations, competitive environment, and impacts in the local communities [10]. In addition to balancing the multiple needs related to using forest resources in primary production [11], enhancing the ecological and socio-economic sustainability of forest-based bioenergy and its markets also requires paying attention to the sustainability effects caused by different phases of the production [12]. Abreast with the ecological, economic and social issues, the importance of recognizing cultural sustainability as an independent dimension of sustainability has gained more attention since the 1990s [13–17].

Compared to social sustainability, cultural sustainability is more context-dependent, describing particular opinions, values and character of a group of people living at a specific time and place [18,17]. For example, forest landscapes do not only have ecological value, but also crucial value in expressing the interactions between society and local livelihood, thus supporting the cultural integration of the local people in the society [19,20]. Especially in the era of industrial globalization, urbanization, and international pressures on using local natural resources in geographical regions rich in natural resources, incorporating culturally acceptable landscape management to secure local cultural systems is becoming more and more important to decrease the threats on the existence of valuable cultural landscapes [21,22,19]. Thus, cultural sustainability does not comprise only places of spiritual importance for some groups of people, for example, but also local traditions in developed countries of using forest resources and acquiring livelihood as workers in the forest sector, for example [17,6,46]. Additionally, from the perspective of climate change, recognizing local cultures of different regions related to their traditions and knowledge on natural resource usage is crucial issue in seeking for global climate change adaptation and mitigation strategies [23].

There is no unambiguous definition for the concept of sustainability, which causes challenges for the empirical assessment of the overall sustainability impacts of natural resource usage decisions [24,25]. In the report of Brundtland [26], for example, sustainability is defined in general as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs". Similar to the concept of sustainability, the definition of sustainable development is also a complex entity including ecological, economic, technological, social, political and human dimensions of the development [27,28].

Sustainable development may be approached from macro-regional (e.g., continents), national, and micro-level (i.e., communities, firms and households) perspectives [29]. In forestry, the sustainable use of forest resources at macro-level presumes taking into account the monetary and non-monetary benefits of forests in general, while at a national and micro-level the sustainable use of forests requires concrete steps towards supporting the socio-economic development enhancing both the conservation of the key features of the ecosystems and the contribution to the fulfilment of human needs in a broad scope [30].

Indicators are tools for aggregating and condensing information used for defining and understanding multi-dimensional relationships between the ecological, economic, social and cultural sustainability dimensions and the different scopes of sustainable development [27]. Ready-made indicators and indicator systems developed for particular assessment situations are usually not suitable for all measurement contexts and therefore require modification in order to serve other/new situations of sustainability evaluation [27,31,32]. The indicator definition and modification may be based either on top-down or bottom-up approaches: top-down indicators are created via political processes [33] and they are applicable especially to macro-level and national decision-making, while the definition of indicators in a bottom-up approach is grounded on local participation for taking into account the micro-level diversity of local circumstances [34,35].

The purpose of this literature review is to map the existing indicator sets introduced in scientific literature suitable for assessing the ecological, economic, social and cultural sustainability of forest-based bioenergy production systems. The focus of this study is especially on literature including local, i.e., micro-level, perspective on sustainability indicators that could be employed in developing bottom-up multi-dimensional sustainability assessment in communities and firms/businesses involved in forest-based bioenergy production. In addition to examining the contents of indicator sets, also the challenges and critical areas in assessing ecological, economic, social and cultural sustainability by using different types of indicators are evaluated.

2. Theoretical background

Principles, criteria, indicators and verifiers are *conceptual tools* for sustainability assessments [36]. Principles are "a fundamental truth" or "a law" used as a basis for a reasoning or action that provides justification for the criteria and indicators. As an example, a principle for using biomass for energy sources could be: "Sustainable bioenergy production has a notable potential for creating environmental, economic and social benefits both at local and global level" [37].

Criteria add meaning and operationality to a principle without being a direct measure of performance, while indicators are variables or components of a system expressing the status of a particular criterion [36]. According to Bossel [38], indicators are linkages to a real world by condensing the enormous amount of meaningful information into a manageable quantity of data usable in decision-making. Indicator sets to be developed for a certain system are determined by two distinct requirements: they must provide vital information of the state of the system and they must provide sufficient information for decision-makers to intervene and correct the system in relation to the given objectives. The state indicators provide information of the current state of the system, while the rate indicators express the speed of change in the system. Verifiers are data, which provide specific details of the

indicators and they may also define case-specific threshold values for the system [36].

In terms of their usability, each set of indicators is usable only as long as the assumptions behind them are valid [39] and the information obtained with them is reliable [40]. Indicators must be reliable and valid in describing the relationships between ecological and human systems comprising economic and socio-cultural aspects [27,41–43]. The most useful indicators are applicable in condensing large amounts of relevant information about the current situation and future developments into a recognizable form [27]. Good criteria reflect the relevant quantities of sustainability measured with indicators. Indicators, in turn, measure parameters that are available from the data in a quantitative or qualitative form [40]. Typically, indicators are numerical measures of physical, economic and social systems [32,33]. They also include information relevant to time [32,40–44] in such a way that it enables the monitoring of the changes and development in sustainability.

The assessment and planning purposes may require indicators to have some threshold values indicating the success or the failure to support or promote the measured parameter [44]. In the case of weak sustainability, success in the performance of one sustainability measure can compensate failure in other measures, whereas in the case of strong sustainability compensation is not accepted. As a result, supporting strong sustainability requires not only the definition of threshold values for the indicators within a particular sustainability dimension [45], but also the recognition of trade-off impacts in-between different sustainability dimensions caused by natural resource usage decisions [54]. In terms of promotion, indicators are also an expression of values helping to create a picture of the desired environment and society that is to be protected and promoted [27]. In addition, the values of indicators also provide information of the improvements needed in the quality of life while simultaneously staying within the environmental carrying capacity [39].

Challenges in the employment of indicators are caused by the complex natures of the concepts “sustainability” and “sustainable development” [24,25,27,29]. In addition, even similar systems (e.g., forest-based bioenergy production chains) interact with their external environment in different ways depending on their geographical location, for example, and the scope of measurement (e.g., macro-regional vs. micro-level) [27]. As a result, there is a need to define separately sets of indicators to different sustainability measurement situations. This, in turn, creates a new problem: if not all indicators give the same positive or negative sign in the evaluations, it is more demanding to ascertain whether the process of sustainable development has been progressing or not [39]. For example, in terms of social sustainability, the presence of large companies may have in one assessment context positive impacts on the vitality of a region, while in another context they may depress local livelihood [54].

Connected to the sustainability measurement situations, the weakness of the top-down indicators is the fact that they may miss critical sustainable development issues at a local level leading to failures in measuring the important issues for local communities [47]. According to Elgert and Krueger [48], top-down indicators developed in global political processes seeking for compromises may even have adverse impacts on sustainable development by representing limited views on local sustainable development agendas. Additionally, in forest-related activities, a challenge of the sustainability assessments is the fact that at community-level many aspects related to diverse multiple-uses natural resources are intertwined between different interest groups [30]. To enhance the acceptability of natural resource decisions in the long-term, local stakeholder views and management priorities should be taken into account in the sustainability indicator definition processes [49] In addition, locally perceived impacts caused by changes in the forest products trade, for example, may also differ considerably from the general, macro-level effects occurring in large regions [50].

In a bottom-up criteria and indicator selection for a particular case, sustainability assessment sets developed in similar contexts are an appropriate starting point for an indicator and measurement system construction [36]. In addition, from the perspective of national and macro-regional sustainable development, it is crucial that the results of bottom-up processes are aggregated into formal top-down processes [51]. Increasing the practical and political usability of indicator sets requires interplay with these two perspectives [40], especially in assessing the sustainability effects related to forest resource usage [52]. So far, most of the sustainability measurement systems have been developed in top-down processes leading to many deficiencies in their applicability to practical evaluations implemented at a local level. In addition, without well-defined expectations for local benefits, motivation within a community to invest in data gathering and sustainability monitoring is impeded [32]. Thus, in order to increase the effectiveness and applicability of the local multi-dimensional sustainability assessment systems, new measurement approaches are needed [43].

3. Material and methods

The material of the study comprises peer-reviewed research articles published in the 1990s and 2000s in international peer-reviewed scientific journals focused on criteria, indicators and sustainability assessment systems linked directly or indirectly with bioenergy production based on using the wood resources of boreal and temperate forests. Research articles approaching sustainability measurement were gathered up in May 2014 with a systematic literature review in four electronic databases (ScienceDirect, Wiley Online Library, IngentaConnect and Academic Search Complete (EBSCO)) by using search words for titles, abstracts and keywords. For the comparability of searches, all electronic databases selected for material gathering had similar advanced search options to scan the articles.

In the literature searches, a special aim was to concentrate on the micro-level perspective, although national and macro-regional scopes were also taken into account when the contents of the articles seemed to be relevant from the objectives of this study. In addition, since bioenergy processing is closely interlinked with primary production in forestry and energy industries in general [55], empirical research related to sustainability measurement within these fields were also included in the material gathering from the electronic databases. Related to the conceptual tools of sustainability assessments, information on criteria and indicators was a main concern in the literature searches compared to information on principles and verifiers. In recognizing the sustainability assessment systems useful from the perspective of this study, criteria and indicators were assumed to provide more operationality and meaningfulness than principles with high generality and verifiers with strong context dependent specificity.

The data gathering for sketching the existing sustainability assessment systems and measures relevant from the perspective of this study was implemented with a systematic literature review methodology. Prior to the systematic literature review, the search words to be used in the database searches were identified by using previous literature on the topic of the study. The actual systematic literature review of this study comprised three steps. In Step 1, the database searches were implemented in ScienceDirect, Wiley Online Library, IngentaConnect and Academic Search Complete (EBSCO) to seek for articles relevant from the perspective of this

study. In Step 2, the abstracts of the articles identified in Step 1 were thoroughly examined to select studies for further scanning in Step 3. In order to avoid selection bias resulting from too strict a selection procedure, all abstracts with even seemingly weak relevance from the perspective of this study were selected for Step 3. In Step 3, the whole contents of the articles selected in Step 2 were studied to identify the initial set of articles for the material of this study.

Step 1 comprised 32 rounds of database inquiries with different combinations of 18 search words within each of the four electronic databases. A detailed description of the search words used in Step 1, the number of hits received in search rounds in separate electronic databases, and the cumulative sums of hits for all electronic databases in total are presented in Table 1. If any of the database searches resulted in more than 300 hits, the search was refined by adding one search word at a time in order to delimit the search hits into a more manageable amount of abstracts to be evaluated.

In Step 2, an in-depth scanning was implemented for the abstracts with indications of profoundly approaching sustainability criteria and indicators as well as sustainability measurement systems connected directly or indirectly with forest-based bioenergy production systems. As a result, 106 peer-reviewed articles were identified for thorough examination in Step 3.

As an outcome of Step 3, 13 articles were found with a specific focus on criteria and/or indicators applicable for assessing the sustainability of the forest-based bioenergy production from a local perspective. The systematic literature review process to find the 13 articles forming the initial material of this study is illustrated in Fig. 1, and a detailed description of the contents of the 13 articles is presented in Table 2.

4. Results

4.1. Characteristics of the reviewed articles

The empirical focus of the 13 articles composing the material of this study is either in bioenergy production systems, energy systems in general, or forest management. In five of these articles the sustainability assessment frameworks are merely based on literature reviews [55,56,49,65,66], while seven of them are grounded on empirical data [57–62,64] gathered by using expert views, for example.

In six of the articles the focus is both on the environmental, economic and social dimensions of sustainability, while in five studies the emphasis is on one dimension of sustainability, i.e., the ecological aspects of forestry [64], wood-fuel production [55] and bioenergy systems [63], social sustainability of energy technologies [58], and cultural sustainability of forest energy production [62]. In addition, in two of the studies there is a focus on bi-directional sustainability, i.e., socio-cultural aspects of natural resource sector planning [61] and socio-economic aspects of bioenergy systems [65]. In this review, the research papers introduced in Table 2 are used for compiling the criteria and indicators especially suitable for approaching with a bottom-up perspective the assessment of the ecological, economic, social and cultural sustainability of forest-based bioenergy production.

The meanings of principles, criteria, indicators and verifiers as *conceptual tools* for sustainability assessments are unambiguous from a theoretical perspective [37]. In contrast, when dealing with empirical sustainability assessment systems either based on literature or empirical data, no unambiguous four-level classification rules exist for them. The ambiguity in the classification rules of the conceptual tools leaves much space for personal judgments that is evident also in the articles reviewed in this study. As a result of the differences in the classifications made for the conceptual tools in the reviewed articles, compiling the results of this study has not been entirely straightforward. In some cases there has been a need for harmonizing the original information to achieve a coherent outcome.

The differences in the classifications and the contents of the conceptual tools introduced in the reviewed articles comprise the following aspects: First, in Buchholz et al. [57] sustainability assessments are classified into criteria and explanations, of which some can actually be considered as indicators (e.g., “number of jobs created” as an explanation of a criterion in the economic sustainability dimension). Second, Lattimore et al. [55] comprises all four levels of conceptual tools for sustainability assessments, i.e., principles, criteria, indicators and verifiers, and it also includes suggestions for applying the indicators at different levels of decision-making (i.e., international, national, sub-national and forest management unit). The indicators representing a forest management unit (FMU) and their verifiers are the most congruent ones with the indicators introduced in other reviewed articles, and thus the FMU indicators are presented in the results of this study. Third, in Axelsson et al. [61], both criteria, indicators and verifiers are introduced, but in comparison with other articles composing the initial material of this study, the elaborateness of the criteria, indicators and verifiers in their study is similar to the principles, criteria and indicators in the other studies.

The ecological, economic and social indicators in Tables A1–A3 are classified according to the criteria of Buchholz et al. [57], presenting a multi-dimensional approach (i.e., including ecological, economic and social perspectives) to the sustainability assessments of bioenergy production. In addition, to classify cultural indicators at the level of the criteria in Table A4, information on cultural sustainability classifications used by Axelsson et al. [61] are employed abreast with cultural sustainability criteria (“cultural acceptability” and “visual and noise impacts”) introduced by Buchholz et al. [57] within a social sustainability dimension. Outside of combining some original criteria into a new criterion and moving cultural acceptability criteria from a social sustainability dimension into a separate dimension of cultural sustainability, the information contents of Buchholz et al. [57] have not been modified in the results of this study (Tables A1–A4).

In the results of this study, the differences in the conceptual tool classifications presented in the reviewed literature have required some information restructuring. In some instances, information presented at the level of verifiers in an original source has been reorganized in this study into the level of indicators. In addition, in some occasions indicators have been classified into a sustainability dimension differing from the original source. For example, although Lattimore et al. [55] have introduced “Concrete, appropriate and efficient means to interest various stakeholders in protecting the forest against unsustainable fuelwood harvesting” (Indicator 7.2) as an ecological indicator, in comparison with the information of the other reviewed articles it fits better in the social dimension. However, outside from some reorganization made for the classifications of the conceptual tools, the descriptions of the contents of the conceptual tools have not been modified in the results of this study.

4.2. Criteria and indicators suitable for assessing the sustainability of forest-based bioenergy production

The literature analysis resulted in identifying 165 ecological indicators [55,56,49,58,60,63,64,66] at 11 criteria levels (Table A1), 45 economic indicators [56,49,58,60,65,66] at 4 criteria levels (Table A2), 66 social indicators [56,58,59,60,61,65,66] at 10 criteria levels (Table A3), and 24 cultural indicators [57,59,61,62] at five

Table 1
The usage of search words in different search rounds, the number of hits received in Step 1, and the number of abstracts found in Step 2.

SEARCH WORDS USED IN SEARCH ROUNDS	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	TOTAL
Sustainability		x	x				x	x	x	x	x	x	x	x	x	x	x		x	x					x		x	x	x	x			20
Indicators						x	x	x	x				x								x					x			x	x	x	x	11
Forest	x	x				x	x	x									x	x	x													x	9
Bioenergy	x	x	x	x	x				x		x											x				x							9
Energy												x	x				x	x		x	x		x				x	x					9
Assessment					x					x	x	x	x		x	x						x	x										9
Measurement								x								x														x	x	x	5
Sustainable Development																						x	x			x					x	x	5
System				x	x																						x	x					4
Cultural																								x	x				x	x			4
Standards														x	x	x																	3
Wood																				x	x												2
Ecological																								x	x								2
Economic																								x	x								2
Social																								x	x								2
Criteria																		x					x										2
Fuel																			x														1
Regional																												x					1
ScienceDirect: Total # of hits (Step 1)	394	58	236	762	171	1920	160	-	33	232	86	721	157	692	161	-	123	63	75	95	63	42	67	180		18	147	82	58	-	85	-	
# of abstracts found within search round (Step 2)	*	5	16	*	9	*	17		13	4*	14	*	12	*	4		9	6	4	7	5	7	5	4		5	4	3	3		7		155
# of new abstracts found by search rounds[a] (Step 2)		**5**	**13**		**4**		**12**		**2**		**0**		**3**		**4**		**2**	**1**	**0**	**0**	**1**	**0**	**1**	**2**		**1**	*	**0**	**1**		**4**		**58**
Wiley Online Library: Total # of hits (Step 1)	72	-	65	156	-	785	16	-	5	682	20	129	-	257	-	-	250	14	13	14	15	6	11	111		2	190	-	13	-	8	-	
# of abstracts found within search round (Step 2)	4		7	3		*	1		1	*	1	3		2			6	1	1	3	1	1	2	4		0	2		0		0		45
# of new abstracts found by search rounds[a] (Step 2)	**4**		**5**	**0**			**0**		**0**		**0**	**2**		**2**			**3**	**0**	**1**	**0**	**0**	**0**	**0**	**4**		**0**	**0**		**1**		**0**		**22**
IngentaConnect: Total # of hits (Step 1)	157	-	164	239	-	8990	521	126	20	943	55	677	163	323	769	269	139	14	98	93	148	28	34	260		11	139	184	700	106	783	49	
# of abstracts found within search round (Step 2)	6		10	4		*	*	8	2	7	2	*	3	6	*	2	2	2	2	2	0	0	1	0		1	0	0	*	0	*	4	51
# of new abstracts found by search rounds[a] (Step 2)	**6**		**4**	**1**				**7**	**0**	*	**0**		**3**	*		**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**		**0**	*	**0**		**0**		**1**	**24**
EBSCO: Total # of hits (Step 1)	298	-	171	584	108	2189	104	-	22	236	52	488	110	904	137	-	101	31	47	64	43	12	17	319	44	3	114	72	58	-	53	-	
# of abstracts found within search round (Step 2)	6		10	*	4	*	13		9	2	8	*	11	*	2		7	3	2	3	3	1	1	*	0	0	1	3	2		2		90
# of new abstracts found by search rounds[a] (Step 2)	**6**		**8**		**0**		**11**		**0**	*	**2**		**5**		**2**		**1**	**0**	**0**	**1**	**0**	**0**	**0**		**0**	**0**	*	**1**	**1**		**2**		**54**
# of new abstracts found in ScienceDirect searches[b]		5	13		4		12		2		0		3		4		2	1	0	0	1	0	1	2		1		0	1		4		56
# of new abstracts found in Wiley Online Library searches[b]	4		5	0			0		0		0	2		2			3	0	1	0	0	0	0	4		0	0		1		0		22
# of new abstracts found in IngentaConnect Library searches[b]	4		3	1				5	0		0		1			0	0	0	0	0	0	0	0	0		0		0		0		1	15
# of new abstracts found in EBSCO searches[b]	1		0				3		0		1		2		1		0	0	0	0	0	0	0		0	0		0	1		2		12
Total cumulative # of new abstracts found (Step 2)[b]	**21**		**21**	**1**			**15**	**5**	**2**		**1**	**2**	**5**	**2**	**5**		**5**	**1**	**1**	**0**	**1**	**0**	**1**	**6**	**0**	**1**	**0**	**0**	**3**	**0**	**6**	**1**	**106**

**Title, abstract and keyword search resulted in more than 300 hits; more keywords were added for the next search round.*
[a]Hits for same abstracts in sequential search rounds within the database have been omitted.
[b]Articles were found in two or more databases. In the total number of articles found, the overlapping results of different database searches have been removed.

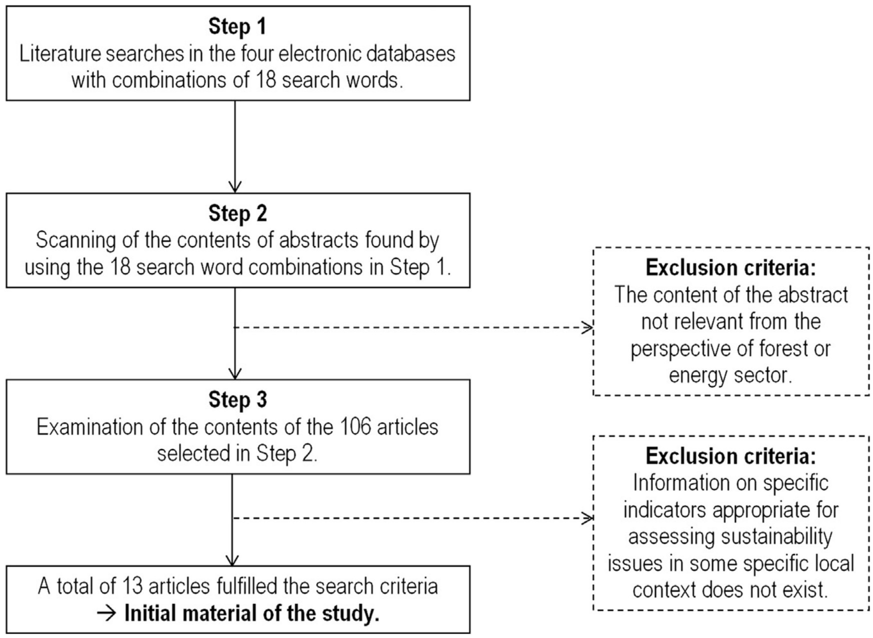

Fig. 1. Implementation of the systematic literature review to compose the initial material of the study.

criteria levels. Due to the large amount of information (294 indicators in total), Tables A1–A4 are presented in Appendix A.

In all, approximately half of the indicators presented in the literature were ecological ones, while measures for economic, social and cultural dimensions represented approximately the other half of the sustainability indicators. In Sironen et al. [62], altogether 49 cultural sustainability indicators are presented. However, since many of those indicators overlap with the ecological, economic or social dimension, in Table A4 the focus is merely on the measures providing entirely new information on cultural sustainability assessment in the context of forest energy production as illustrated by Lähtinen and Myllyviita [6].

The larger amount of ecological indicators in contrast to other sustainability dimensions results to some extent from special emphasis on forest management (i.e., primary production) in the ecological dimension when it is not strongly emphasized at indicator level in the economic dimension. In addition, in the ecological dimension, many of the indicators especially within the criteria of "Ecosystems protection, sustaining ecosystems connectivity, adaptation capacity to environmental hazards and climate change" are very similar to each other but not similar enough to have exactly the same contents. Compared to the ecological and economic dimensions, in the social and cultural dimensions the special characteristics of forestry and especially forest-based bioenergy production have gained more attention. For example, within the social criteria of "Planning", "Participation", and "Social cohesion" and the cultural criteria of "Cultural landscape, visual and noise impacts" and "Cultural acceptability", the distinctive characteristics of the forest sector can be perceived. In spite of this, many indicators especially within the social dimension related especially to labor and health issues can be employed in primary production and processing industries independently from the industrial branch, as well.

In measurability, the economic indicators based mostly on monetary units are less ambiguous as an entity than the ecological and social ones comprising also many factors requiring personal judgement in defining the contents of the measures and impact data gathering. The aspects causing the need for qualitative personal judgements in sustainability measurements are emphasized in *Italics* in Tables A1–A3. The problematic measures in the ecological dimension (Table A1) are mainly related to primary production in forests, for example "Land required for *critical* population levels" (Indicator 1.30) and "Species protection and restoration *programs* for endangered, threatened, vulnerable or rare species" (Indicator 2.7). In the social dimension (Table A3) the measurability of "*Necessity* of participative decision-making processes in site selection for energy systems" (Indicator 7.7) and "*Perceived* catastrophic potential" (Indicator 9.3), for example, can be questioned. Similarly, many of the indicators in the cultural dimension comprise ambiguous aspects of sustainability assessments although their contents can be considered to be valid in the context of the forest sector. For example, "*Traditional knowledge* related to forests" (Indicator 3.5) and "*Homogeneity* of practitioners" (Indicator 5.7) are difficult to define and evaluate.

In comparing the indicator information between the four dimensions of sustainability, in general the ecological, social and cultural indicators are less ambiguous in their expression of describing the success or failure in supporting sustainable development. Thus, although leaving simultaneously more space for personal judgements, the qualitative characteristics of the contents of those measures also add value of information in the measures. In contrast, in the economic dimension (Table A2), for example, defining the positive or negative effect of the measures for sustainability is more ambiguous due to the impact of the scope of measuring (e.g., micro-level assessment concerning a firm vs. micro-level assessment concerning a community). For example, at a firm-level the regional raw material costs, i.e., regional accrual for raw material (Indicator 3.6), are not self-evidently a factor of economic sustainability, while at a community-level they support economic well-being. Consequently, both the scope and direction of the measurement (positive or negative) should be defined unambiguously.

Connected to the scope of measurements, the division of criteria and indicators especially between different sustainability dimensions is also ambiguous. Buchholz et al. [57], for example, define "Employment generation" as an economic criterion of bioenergy production chains, although for a firm employment generation is not usually a purpose but a consequence of operations. Yet, employment generation supports the social sustainability of operations both within a firm and community. In

Table 2
The characteristic of the 13 peer-reviewed articles selected in Step 3 for the initial material of this study.

	Focus			Sustainability dimension				Conceptual tools				Approach		Level		
	Bioenergy	Energy	Forestry	Ecological	Economic	Social	Cultural	Principles	Criteria	Indicators	Verifiers	Literature review	Empirical study	Firm(s)	Community	Nation/Region
Article 1[b] [55]	×			×				×	×	×	×	×		×		
Article 2 [56]		×		×	×	×				×		×		×		
Article 3 [49]			×	×	×	×			×	×		×			×	
Article 4 [57]	×			×	×	×			×				×			×
Article 5 [58]	×			×	×	×				×			×	×		
Article 6 [59]		×				×				×			×	×		
Article 7 [60]			×	×	×	×		×	×	×	×		×		×	
Article 8 [61]	×[a]		×[a]			×	×			×	×		×		×	
Article 9 [62]	×		×				×			×			×	×		
Article 10 [63]	×			×					×	×		×		×		
Article 11 [64]			×	×				×	×	×			×			×
Article 12 [65]	×				×	×			×	×		×		×		
Article 13 [66]		×		×	×	×				×		×			×	

[a] In addition, agricultural production and mining were also studied.
[b] Similar issues approached also in Lattimore et al. [67].

contrast, at a community-level employment generation is a factor of positive economic development. Consequently, the viewpoint of the sustainability measurements may affect strongly the interpretation of the results both within a particular sustainability dimension and between separate sustainability dimensions. Similarly, cultural landscape issues are linked to both ecological sustainability assessed, for example, with "Diversity at landscape level in terms of age class structure, structural variation, variation in different types of ecosystems" (Indicator 1.1) and cultural sustainability evaluated, for example, with "Scenery change because of harvesting residue" (Indicator 2.2). As leaving harvesting residues increases ecological sustainability (e.g., Indicator 1.26), there are conflicting goals between different sustainability dimensions approaching landscape issues from different stakeholder perspectives. Furthermore, some of the ecological indicators related to natural resource efficiency seem to be economic indicators such as "Land base available for timber production" (Indicator 7.6). Indicators related to efficient resource utilization cannot be unambiguously defined as ecological indicators since in many cases the main target of efficiency is to decrease costs, not to preserve natural resources.

The results in Tables A1–A4 show that the amount of indicators available for developing bottom-up measurement of the sustainability of forest-based production chains is numerous and to some extent even complex, while at criteria-level the information is more structured. Furthermore, multi-dimensional measurement frameworks taking into account simultaneously at indicator-level the aspects of the ecological, economic, social and cultural development have not been presented in the existing research literature. In addition, cultural issues as an individual dimension in enhancing sustainable development and especially in the context of the forest sector have gained more attention only in previous years.

5. Discussion

The purpose of this study was to scrutinize the ecological, economic, social and cultural indicators presented in scientific literature suitable for assessing the sustainability of forest-based bioenergy production from a local perspective. Additionally, critical areas in employing different types of ecological, economic, social and cultural sustainability indicators to evaluate the sustainability impacts of forest energy production were evaluated.

Compared to global indicators developed in top-down political processes, developing bottom-up sustainability assessment can provide more profound information on the local development challenges to be solved when aiming to meet the global goals of sustainable development [68]. The local impacts of forest resource usage, for example, in the context of energy production vary considerably in different societies and geographical regions. Thus, the fulfilment of local sustainability agendas and increasing the acceptability of forest energy production can be supported with an inclusion of ecological, economic, social and cultural characteristics of particular regions in the sustainability assessment and reporting. In addition, these multi-dimensional effects of forest-based energy production should be evaluated within the whole life-cycle of the products and services from primary production to waste management or recycling.

The results of the study show that the amount of indicators available for assessing at micro-level the ecological, economic and social sustainability of forest-based bioenergy production is numerous. In addition, in previous years measures for evaluating the cultural sustainability of forest energy production have also been introduced. So, the main question in the assessment of local sustainability in the context of forest-based bioenergy production

does not lie so much in the development of new indicators, but in the selection of the most appropriate ones from the viewpoint of (1) local development goals, challenges and opportunities, (2) the perspective of local assessments (e.g., firms vs. communities) (3) trade-offs in different sustainability dimensions caused by forest-based bioenergy production decisions and (4) impacts of those decisions in time.

Regarding the selection of indicators appropriate from the perspective of local development goals, at the moment comparable research information on the role of local circumstances in selecting the local indicators within different societal and/or geographical contexts does not exist. In addition, the results of this study show that the availability of local-level indicators available for assessing different phases of forest-based bioenergy production is not in balance. While in the ecological, social and cultural dimensions there is a higher emphasis on primary production, in the economic dimension the focus is more on the primary and secondary processing of products. In terms of assessing the economic sustainability of forest-based bioenergy production, including transparently the role of primary production would be crucial, since energy wood production in particular is highly affected by subsidies paid for forest owners, for example [69]. Similarly, also within the ecological, social and cultural dimensions the assessment of different phases of value-chains should be balanced. For example, global changes in the forest sector do not affect only the cultural traditions of forest owners selling wood, but also the employees working in traditional forest industry businesses [source].

Consistency of the indicators and criteria within and between the sustainability dimensions is a crucial part of the validity and reliability of the sustainability assessments in forest-based bioenergy production. In the context of this study, consistency can be regarded as a balance between sustainability measures describing different phases of production from primary production to processing and end-use in each sustainability dimension. In addition, the scope of measurements (e.g., firm-level vs. community-level) should be the same between indicators within a particular sustainability assessment framework. For example, between the economic and social dimensions the risk of double-accounting can be decreased with a clear definition of the scope of sustainability measurements (e.g., firm-level vs. community-level). In addition, since information on separate cultural indicators is still scarce, new information is needed on the distinct characteristics of cultural sustainability especially in relation to social sustainability aspects. However, even with a well-defined scope of measurements there are discretionary problems to be solved when developing multi-dimensional sustainability assessment frameworks. Employment generation, for instance, supports not only economic well-being but also social livelihood. In spite of this, criteria and indicators related to employment generation must somehow be divided between these sustainability dimensions to avoid the risk of double-accounting.

Personal judgements related especially to qualitative information gathering pose challenges to the measurability of the results. On the other hand, the results of the study show that qualitative measures have approached the kinds of issues in sustainable development that quantitative indicators are lacking. For example, aspects of participatory decision-making are important in making forest-resource usage decisions at local level [68], although their quantification is challenging. Similar to the consistency related to the different dimensions of sustainability and phases of production, also the coherence between the quantitative and qualitative measures can be increased with a clear scope definition. In a bottom-up approach, qualitative aspects can also be modified into measurable ones, for example, if the context of the measurements is clearly defined providing profound information on the actual implementation of the participatory decision-making.

In general, decision-making related to forest industries concerns difficult multi-criteria and value-laden problem solving with interactions to economic, employment and energy, and environmental policies [70]. To some extent, the application of multi-criteria decision-making (MCDA) methodologies can provide support for practical sustainability assessment situations in the context of forest-based bioenergy production [71]. In forest resource management, the MCDA can be employed, for example, to define a set of sustainability indicators with a stakeholder interaction, to assess the relative importance of different sustainability indicators in specific local sustainability assessment contexts and to identify the interactions between different indicators [72]. In addition, at a more general level of assessing the impacts of the usage of biomass for energy, Buytaert et al. [73] have tested the possibilities to employ life-cycle assessment (LCA), environmental impact assessment (EIA), cost–benefit analysis (CBA), energy analysis (EA), and system perturbation analysis (SPA) to implement comprehensive sustainability analysis. Although by combining several comprehensive methodologies to implement sustainability analysis on the impacts of natural resource decisions may be acquired in the future, without a well-defined scope of measurements the application of any assessment methodologies do not bring any extra value for the sustainability assessments [73].

In the future, it would be crucial to develop concrete methodologies that provide comprehensive grounds both for the definition of multi-dimensional bottom-up indicators and the assessment processes in the context of forest-based bioenergy production. The results of the study show that there are plenty of indicators suitable for micro-level sustainability assessments related to bioenergy firms and communities dependent on forest resources. However, their empirical application is challenged both by many non-uniformities in the practical classification of sustainability assessment tools, i.e., principles, criteria, indicators and verifiers, and by the deficiencies in their concrete conceptual definitions. In addition, to a large extent also the linkages between the ecological, economic, social and cultural sustainability dimensions are not well defined in the assessment systems.

In order to condense the huge amount of information within the existing research literature, new research input will be needed to concretize the implementation of the indicator definition in specific societal and geographical contexts of the forest sector, data gathering methodologies and sustainability assessment processes. Simultaneously with the need of comprehensive analysis of the sustainability trade-offs and possible pathways for increasing global bioenergy production, inter-regional comparisons are required to acquire information on the impacts of biomass-based energy production operations in different regions [74].

The results of this study show that the amount of indicators relevant for assessing the ecological, economic, social and cultural sustainability of forest-based energy in different local contexts is large. On the other hand, they are not probably equally important in different geographical areas even with similar societal circumstances. For example, assessing social sustainability with percentage of forest in urban areas (Indicator 6.5) is probably not as relevant in highly forested, sparsely populated Nordic countries as in some more populated Central European countries. In spite of this, both Nordic and Central European countries share the same general global sustainability goals related for bioenergy production, for example.

To some extent top-down indicators developed in political top-down processes are sufficient in assessing the sustainability impacts of forest-based bioenergy production, for example, in the European Union (EU) countries. Yet, the circumstances are

not identical between the EU countries, nor between different regions (e.g., rural vs. urban areas) within different EU countries. Thus, information received by using the top-down indicators could be supplemented with information related to selected bottom-up indicators that are related to the most critical issues in different localities. Abreast with increasing the acceptability of forest-based production in general, profound understanding of local environmental, economic, social and cultural sustainability impacts could increase the motivation for development and involvement in distributed energy production in the regions rich of forest resources, for example. The comprehensive indicators lists presented in this study can be employed as background information to define the measures that are especially relevant in enhancing the local sustainability goals from the perspective of different stakeholders in specific localities.

Appendix A

See Tables A1–A4.

Table A1
Ecological criteria and indicators introduced in the original references.

Ecological sustainability

(1) **Ecosystems protection, sustaining ecosystems connectivity, adaptation capacity to environmental hazards and climate change** [57] **(3 criteria combined)**

1.1 diversity at the landscape level in terms of age class structure, structural variation, variation in different types of ecosystems [55]
1.2 number of naturally regenerating native woody species [64]
1.3 cover and abundance of the natural regeneration per species [64]
1.4 conversion of natural forests to short-rotation woody crop plantations is not practiced [55]
1.5 area of natural forests converted to plantations after 1994 [49]
1.6 percentage of forest biomass sourced from certified forests [49]
1.7 ecologically sensitive areas are protected [60]
1.8 number of times harvesting activities undertaken for biomass impact protected or critical wildlife areas at the harvest site or adjacent areas [49]
1.9 number of days biomass harvesting coincides with critical wildlife breeding season [49]
1.10 level of forest fragmentation and connectedness of forest components [60]
1.11 percentage of open spaces [64]
1.12 stem distribution [64]
1.13 mixing index of Von Gadow [64]
1.14 number of vegetation layers [64]
1.15 height differentiation index of Von Gadow [64]
1.16 total aboveground mass of the woody vegetation [64]
1.17 leaf area index [64]
1.18 number of thick trees per hectare [64]
1.19 number of very thick trees per hectare [64]
1.20 road network density, type and use [60]
1.21 extent to which forest management *considers* the protection of unique or significant landscape level features [60]
1.22 area of *representative* protected areas for *enabling* natural processes as well as habitat and species conservation [60]
1.23 area/severity of natural disturbances such as storm, insects and wildfire [60]
1.24 sustainable residue extraction levels exist in national/local guidelines [55]
1.25 percentage of harvesting residues left at site [49]
1.26 coarse wood debris and snags retained at *functional* levels [60]
1.27 number of snags and den trees per acre left on site [49]
1.28 number of dead thick and fallen trees per hectare [64]
1.29 percentage of surface area consisting of dead standing trees [64]
1.30 land required to maintain *critical* population levels [55]
1.31 connectivity among habitats on the landscape [55]
1.32 managing biomass for bioenergy *consistently* with conservation objectives; habitats are of sufficient area to be effective for all species, providing for designation of protected areas and high-conservation forests, protected areas and high conservation-value forests have sufficient buffer-zones [55]
1.33 *susceptibility* of monocultures to catastrophic failure [57]
1.34 *effects* of monocultures on landscape and wildlife [57]
1.35 area of vegetation types and structural classes relative to historical condition and total forest area [60]
1.36 *representation* of selected key and sensitive guilds occur in the community guild structure [60]

(2) **Species protection and crop diversity** [57] **(2 criteria combined)**

2.1 a catalog/database of local species and their requirements exists the catalog is updated regularly and is used to *inform* management plans [55] including information of habitat needs [55], threatened and endangered status of species [55], critical population levels and current population estimates [55]
2.2 number of indigenous species classified as extinct, extirpated, endangered, threatened or vulnerable relative to the total number of indigenous species [60]
2.3 population levels and diversity of local species of flora and fauna are monitored and do not decrease beyond the historic range of variability [55]
2.4 percentage of surface area of native species [64]
2.5 number of native wood species [64]
2.6 populations of indigenous species are *likely* to persist [60]
2.7 species protection and restoration programs for endangered, threatened, vulnerable or rare species [60]
2.8 number of red-listed non-woody vascular plant species [64]
2.9 number of native non-woody vascular plants [64]
2.10 Fagers' NMS index of diversity [64]
2.11 number of fungi species [64]
2.12 number of lichen species [64]
2.13 number of functional groups of bacteria [64]
2.14 specific strategies for maintaining habitat for rare species and/or restoring degrading ecosystems are followed [49]
2.15 presence of taxa of special concern [63]
2.16 habitat area in hectares of taxa of special concern [63]
2.17 health condition of forest crowns [63]
2.18 height/diameter ratio [63]
2.19 cover of pest species [63]

Table A1 (*continued*)

Ecological sustainability
(3) **Exotic species applications and use of genetically modified organisms** [57]
3.1 area and severity of occurrence of exotic species detrimental to forest condition [60]
3.2 population sizes and reproductive success of indigenous species are *adequate* to maintain levels of genetic resources and diversity [55,60]
3.3 use of natural regeneration and of scientifically-based seed transfer rules and seed orchard zones in planting native species [60]
3.4 *negative* ecological *impacts* do not result from the use of genetically modified organisms [55]
3.5 management does not *significantly* change gene frequencies [60]
(4) **Land use change and soil protection** [57] **(2 criteria combined)**
4.1 area of forest land converted to non-forest cover [60]
4.2 soil cover per forest layer [64]
4.3 soil sealing per hectare [64]
4.4 penetrable depth for roots [64]
4.5 Ellenberg mR $\times$ mN ecological spectrum [64]
4.6 earthworm biomass per hectare [64]
4.7 humusindex of Ponge [64]
4.8 functional bacterial diversity [64]
4.9 area of harvested area with degraded soil quality [60,49]
4.10 frequency of biomass harvesting in sites having steep slopes ($>35°$) and the area (in acres) in which such harvesting takes place [49]
4.11 frequency of biomass harvesting in sites where bedrock is within 20 in. of soil surface and the area (in acres) in which such harvest takes place [49]
4.12 area of permanent roads and landings [49]
4.13 area of temporary harvesting infrastructure such as access roads and skid trails [49]
4.14 area and percent of land where forest floor, litter layer and root system removal takes place during biomass harvesting [49]
4.15 soil nutrient status, temperature, structure and processes are maintained within the historic range of variability or are improved [55]
4.16 the biomass harvest is undertaken in season that avoids increased soil erosion sue to rains in dry soils or helps in limiting pest problems [49]
4.17 total organic carbon (TOC); mg/ha [63]
4.18 total nitrogen; mg/ha [63]
4.19 extractable phosphorus; mg/ha [63]
4.20 bulk density; g/cm^3 [63]
4.21 soil cover per forest layer [63]
(5) **Water management** [57]
5.1 there is no *significant* change in the quantity and quality of water from the forest catchment [60]
5.2 practices should *ensure* water conservation and improvement [55]
5.3 maintaining or improving quality and quantity of surface and groundwater within the historic range of variability [55]
5.4 total volume of drainage and/or irrigation channels per hectare [64]
5.5 Ellenberg mF ecological spectrum [64]
5.6 area and percent of water bodies or stream lengths in and around biomass harvesting sites with significant changes in physical, chemical, or biological properties from reference conditions [49]
5.7 volume/weight of biomass harvesting that is undertaken in riparian zones [49]
5.8 measures to avoid pollution of ground and surface water are undertaken, including restricting biomass harvesting from streamside management zones
5.9 compliance with state best management practices [49]
5.10 nitrate concentration in streams (and export); concentration mg/L; export kg/ha/year [63]
5.11 total phosphorus concentration in streams (and export); concentration mg/L; export kg/ha/year [63]
5.12 suspended sediment concentration in streams (and export); concentration mg/L; export kg/ha/year [63]
5.13 herbicide concentration in streams (and export); concentration mg/L; export kg/ha/year [63]
5.14 peak storm flow; L/s [63]
5.15 minimum base flow; L/s [63]
5.16 consumptive water use (incorporates base flow); feedstock production m^3/ha/day; biorefinery m^3/day [63]
(6) **Use of chemicals, pest control and fertilizer** [57]
6.1 pollutant levels (e.g., airborne pollution) and chemical contamination (e.g., pesticides) in the forest ecosystem [60]
6.2 intensity of biocide use [65]
6.3 intensity of fertilization and/or limiting [65]
(7) **Natural resource efficiency** [57]
7.1 area required/unit raw material input [58]
7.2 aboveground net primary productivity (ANPP)/yield; g C/m^2/year [63]
7.3 regeneration and resilience, based on Competitive, Stress-tolerant or Ruderal-strategy (CSR) [64]
7.4 free net primary production [64]
7.5 additional or all year area cultivated in ha/unit raw material input [58]
7.6 land base *available* for timber production [60]
7.7 mean annual increment for forest type and age class [60]
7.8 annual and periodic removals of timber and non-timber forest products by area and /or volume relative to sustainable levels [60]
7.9 annual harvest of wood products by volume and as a percentage of net growth [49]
7.10 biomass harvesting frequency [49]
7.11 roads and infrastructure specific to biomass harvesting are developed at harvest site [49]
7.12 number of times vehicles re-enter the biomass harvest site [49]
7.13 number of times vehicles pass through recently planted sites [49]
7.14 recreational use management *provides* recreational services while minimizing impacts on wildlife and environment [60]
7.15 silvicultural systems are *appropriate* to forest type, production of desired products and condition, and assure forest establishment, composition and growth [60]
7.16 harvesting systems and equipment *match* forest conditions in order to reduce impact on wildlife, soil productivity, residual stand conditions and water quality and quantity [60]
7.17 wildlife management provides hunting, trapping and fishing *opportunities* and is ecologically oriented and sustainable [60]
7.18 *availability* and use of recreational opportunities are maintained and other non-timber values are *provided* [60]

Table A1 (*continued*)

Ecological sustainability
7.19 per capita wood consumption [55]
7.20 firewood production/management area [55]
7.21 amounts of biomass extracted for charcoal production [55]
7.22 industrial bioenergy feedstocks/management area [55]
7.23 extent and nature of illegal harvesting practices [55]
7.24 existence of efficient measures to monitor and protect against illegal harvesting [55]
7.25 amount of carbon steel in tons, used in the construction of the plant/energy produced in lifetime [56]
7.26 amount of copper in tons, used in the construction of the plant/energy produced in lifetime [56]
7.27 amount of aluminum in tons, used in the construction of the plant/energy produced in lifetime [56]
7.28 depletion of non-renewable energy sources [65]
7.29 fossil energy return on investment (fossil EROI); ratio of fossil energy inputs to amount of useful energy output (MJ) [65]
(8) **Energy balance** [57]
8.1 amount of fuel consumed in tons divided by the energy produced in lifetime [56]
8.2 Ellenberg mL ecological spectrum [64]
8.3 primary energy use per capita [66]
8.4 final energy use by sector [66]
8.5 ratio of local renewables production to local consumption of energy and electricity [66]
8.6 industrial energy intensity [66]
8.7 agricultural energy intensity [66]
8.8 service/commercial energy intensity [66]
8.9 household energy intensity [66]
8.10 transport energy intensity [66]
8.11 public transit ridership [66]
8.12 renewable energy share in energy and electricity [66]
8.13 share of household income spent on fuel and electricity [66]
(9) **Waste management** [57]
9.1 amount of waste in tons produced by the plant divided by the energy produced in lifetime [44]
(10) **Greenhouse gas balance** [57]
10.1 amount of carbon dioxide in tons produced by the plant/energy produced in lifetime [44]
10.2 CO_2-equivalent emissions (CO_2 and N_2O); kg C_{eq}/GJ [65]
10.3 reduced CO_2-equivalent by substitution of mineral fertilizer/unit energy input [58]
10.4 reduced CO_2-equivalent by substitution of mineral fertilizer/unit raw material input [58]
10.5 reduced CO_2-equivalent/MWh [58]
10.6 reduced CO_2-equivalent/unit raw material input [58]
10.7 reduced CO_2-equivalent/unit energy input during lifetime of the plant [58]
10.8 estimated total of GHG emissions avoided by using forest biomass for energy, as calculated using a life-cycle analysis [49]
10.9 indirect land use change effects are included in estimating total GHG emissions [49]
10.10 GHG emissions from energy use, per capita and per unit of GDP and by sector [66]
(11) **Potentially hazardous atmospheric emissions other than greenhouse gases** [57]
11.1 emissions of other gases [45], e.g., SO_2 [44], [MB], NO, CO [57]
11.2 amount of nitrogen oxide in tons produced by the plant divided by the energy produced in lifetime [56]
11.3 amount of sulfur dioxide in tons produced by the plant divided by the energy produced in lifetime [56]
11.4 other significant air emissions by type and weight [56]
11.5 tropospheric ozone; ppb [63]
11.6 total particulate matter less than 10 $\mu g/m^3$ diameter ($PM_{2.5}$) [63]
11.7 total particulate matter less than 2.5 $\mu g/m^3$ diameter (PM_{10}) [63]

Table A2
Economic criteria and indicators introduced in the original references.

Economic sustainability
(1) **Economic stability** [57]
1.1 amount of money invested in the respective option divided by the energy production in lifetime [56]
1.2 total investment in €/€ alternative total export of financial funds for external energy acquisition [58]
1.3 regional total accrual in €/€ alternative total export of financial funds for external energy acquisition [58]
1.4 *existence* of economic rents exist [for forest primary production], i.e., total management revenues exceed management costs [60][a]
1.5 economic *importance* of forest management units [forest primary production] for local communities [60][a]
1.6 percentage of money generated by the bioenergy venture remaining in local economy [49]
1.7 number of respective entity/kWh produced in lifetime [56]
(2) **Macroeconomic sustainability** [57]
2.1 national investment / unit input [58]
2.2 total investment/unit input [58]
2.3 regional investment (regional accrual of funds once) unit input [58]
2.4 regional turnover (yearly accrual of funds)/€ total investment [58]
2.5 gain of GNP [45] for the community/unit kWh [58]
2.6 locally available finance schemes for energy efficiency and renewable energy [66]
2.7 return on investment (ROI) [65]

Table A2 (*continued*)

Economic sustainability	
2.8	net present value (NPV) [65]
2.9	terms of trade; price of exports/price of imports ratio [65]
2.10	trade volume; net exports or balance of payments [65]
2.11	the amount of capital/kWh produced in lifetime [56]
(3) **Microeconomic sustainability** [57]	
3.1	regional turnover (yearly regional accrual)/ unit input (material flows) [58]
3.2	profits/acre are accruing from biomass harvesting for energy purposes [49]
3.3	regional turnover (yearly regional accrual) from raw material/unit regional input (material flows) [58]
3.4	average revenue/unit total input (material flows) [58]
3.5	regional raw material costs (regional accrual for raw material)/unit regional input [58]
3.6	efficiency of the system/energy production [56]
3.7	bioenergy venture is reported to be profitable for contractors and processors [49]
3.8	a long-term profitability plan for the venture is put in place [49]
3.9	amount of government support per acre or ton [49]
(4) **Employment generation** [57]	
4.1	number of paid h/kWh produced in lifetime [56]
4.2	generated jobs/unit input [58]
4.3	generated regional jobs/unit input [58]
4.4	number of full-time equivalent (FTE) jobs [65]
4.5	ratio of green energy jobs to population [66]
4.6	employment of local people at forest management units [primary production] [60]
4.7	additional generated and preserved jobs / unit input [58]
4.8	reserved regional jobs/unit input [58]
4.9	displaced regional jobs/unit input [58]
4.10	total [employment] deployment/unit input [58]
4.11	placement of regional personal/unit input [58]
4.12	placement of high qualified regional personal/unit input [58]
4.13	placement of regional personal qualified in the project/unit input [58]
4.14	placement of low qualified regional personal/unit input [58]
4.15	*capacitated* personal/unit input [58]
4.16	household income, dollars per day [65]
4.17	additional generated and preserved jobs/unit regional input [58]
4.18	additional generated and preserved jobs/unit alternatively external purchased energy [58]

[a] In the original source classified into the social dimension.

Table A3
Social criteria and indicators introduced in the original references.

Social sustainability	
(1) **Compliance with laws** [57]	
1.1	forest management *considers and meets* legal forestry requirements and standards [60]
1.2	extent to which forest management *considers and meets* legal obligations concerning duly established Aboriginal and treaty rights [60]
(2) **Planning** [57]	
2.1	*capacity* to implement international instruments and guidelines [55][a]
2.2	*capacity* for research and adaptive management [55][a]
2.3	*capacity* to adequately monitor progress on the ground [55][a]
2.4	there is sustained and *adequate* funding and staff for forest management [60]
2.5	policy and planning are based on recent and accurate information [60]
2.6	objectives are clearly stated concerning major functional forest areas [60]
2.7	institutions responsible for research are *adequately* funded and staffed [60]
2.8	local authority advice and assistance to the citizens on energy issues [66]
2.9	transfer and adaptation of environmentally sound forest management technologies [55][a]
(3) **Monitoring of criteria performance** [57]	
3.1	regular inventories established and monitored regularly [60]
3.2	documentation and records of all forest management activities are kept in a form that makes monitoring possible [60]
3.3	actual vs. planned performance is measured and recorded [60]
3.4	an *effective* monitoring and control systems audits management's conformity with planning [60]
(4) **Standard of living** [57]	
4.1	potential for conflict induced by energy system [59]
4.2	energy security; dollars per gallon of biofuel [65]
4.3	fuel price volatility; standard deviation of monthly percent price changes over one year [65]
4.4	*openness* to new technologies [59]
4.5	technological *flexibility* to incorporate innovations and adaptability to the “future of networks” [59]
4.6	risk of catastrophe; annual probability of catastrophic event [65]
4.7	availability of a *complete* infrastructure for waste disposal [59]

Table A3 (*continued*)

Social sustainability

(5) **Food security and land availability for other human activities than food production** [57] ***(2 criteria combined)***

- 5.1 providing *enough* land locally available for housing, energy (e.g., firewood), recreation and other resource supply [57]
- 5.2 provision of reliable, *adequate* alternative sources of fuel for communities practicing unsustainable fuelwood harvesting [55][a]
- 5.3 area of land available for subsistence purposes [60]
- 5.4 food security; percent change in food price volatility [65]

(6) **Property rights and right of use** [57]

- 6.1 *clear definition* of ownership and use rights and responsibilities to resources (inter- and intra-generational) respecting pre-existing claims [60]
- 6.2 the legal and customary rights of people's to own, use and manage forest öands and resources are recognized and respected [49]
- 6.3 mechanisms exist for sharing economic benefits [60]
- 6.4 *effective* instruments for inter-institutional coordination on land use and forest management exists [60]
- 6.5 living environment (percentage of forest in urban areas)[61][b]

(7) **Participation** [57]

- 7.1 democratic civil society (percentage of participation in local elections) [61][b]
- 7.2 public opinion; percent favorable opinion [65]
- 7.3 awareness rising campaigns on energy issues [66]
- 7.4 transparency; percent of indicators for which timely and relevant data are reported [65]
- 7.5 *accessible* programs to teach rural populations about the importance of sustainable forest management [55]
- 7.6 concrete, *appropriate* and *efficient* means to interest various stakeholders in protecting the forest against unsustainable fuelwood harvesting [55][a]
- 7.7 *necessity* of participative decision-making processes in site selection for energy systems [59]
- 7.8 inclusion of community consultation and traditional ecological knowledge in the development of national, regional and site-specific *best* management practices [55][a]
- 7.9 public participation process should be inclusive with all interests presented [60]
- 7.10 public participation in energy-related policy-making [66]
- 7.11 mechanisms for transparency and public access to information is established and maintained [49]
- 7.12 opportunities are provided for public participation in decision-making related to forests [49]
- 7.13 establishment of a communication system that facilitates exchange of information with stakeholders [49]
- 7.14 effective stakeholder participation; percent of documented responses addressing stakeholder concerns and suggestion, reported on annual basis [65]
- 7.15 stakeholders have *detailed* and *meaningful* reciprocal background information necessary to provide quality input into the public participation process [60]
- 7.16 management staff and stakeholders should *recognize* and *respect* the interests and rights of each other [60]
- 7.17 decision-making process is transparent and *considers* the interests and values of stakeholders [60]
- 7.18 *extent* of Aboriginal participation in forest-based opportunities [60]

(8) **Social cohesion** [57]

- 8.1 access to forest resources is *fair* and secure [60]
- 8.2 *recognition* of economic importance of non-timber values [60]
- 8.3 distribution of rent capture [60]
- 8.4 bioenergy venture (including biomass harvesting) lowers income inequality [49]
- 8.5 human development (index of human development)[61][b]
- 8.6 equity (index of gender development) [61][b]

(9) Respect for human rights [57]

- 9.1 subjectively expected health consequences of normal operation [59]
- 9.2 familiarity with risks [59]
- 9.3 perceived catastrophic potential [59]

(10) **Working conditions of workers** [57]

- 10.1 forestry employer [primary production] *follows* regional, national or international working and safety standards and takes *responsibility* for forest-related health risks of workers [60]
- 10.2 forest management [primary production] *cooperates* with public health authorities concerning forest-related illnesses [60]
- 10.3 total number and rate of employee turnover by age group, gender and region [60]
- 10.4 ratio of skilled to unskilled local people employed in bioenergy production [49]
- 10.5 wages and other benefits conform to regional, national or international minimum standards [60]
- 10.6 The International Organization's eight fundamental conventions are followed [49]
- 10.7 work days lost due to injury [65]

[a] In the original source defined as an ecological indicator.

[b] In the original source the parts without parentheses are defined as indicators and the parts in parentheses defined as verifiers. In comparing the level of generality of indicator definition with the other 13 articles in the material of the study, the indicators are similar to criteria and the verifiers are similar to indicators.

Table A4
Cultural criteria and indicators introduced in the original references.

Cultural sustainability
(1) **Cultural vitality, diversity and conviviality, social capital** [61][a]
1.1 number of voluntary groups; n/1000 inhabitants [61][b]
(2) **Cultural landscape**[a]**, visual and noise impacts (2 criteria combined)** [57][d]
2.1 number of active farmers; n/km^2 [61] [b]
2.2 scenery *change* because of harvesting residue (collection of forest residues increases esthetic value) [62]
2.3 significant *change* in scenery because of increased demand of wood (increased demand for raw material could lead to clear-cutting instead of use of raw material from thinning and residues, causing large-scale changes in scenery) [62]
2.4 peatlands taken into peat production (peatlands are considered culturally significant scenery) [62]
2.5 increase of first thinnings increases esthetic value (first thinnings make the scenery more esthetically pleasing) [62]
2.6 *depletion* of scenery because of storing raw material (stores of raw material can be considered unattractive) []
2.7 functional *impact* of energy infrastructure on the landscape [59][c]
2.8 esthetic *impact* of energy infrastructure on the landscape [59][c]
(3) **Cultural heritage** [61][a]
3.1 historical remains; n/km^2 [61][b]
3.2 spiritual *values* of forests [62]
3.3 extent to which unique or significant sites of social, cultural, spiritual or scientific importance are *considered* in forest management [60][c]
3.4 extent to which forest management *considers* the protection of unique or significant Aboriginal social, cultural or spiritual sites [60][c]
3.5 *traditional knowledge* related to forests (Traditional knowledge related to forests should be maintained) [62]
(4) **Cultural access, participation and consumption** [61][a]
4.1 number of available cinemas, showrooms, theaters, museums and libraries; n/municipality [61][b]
(5) **Cultural acceptability** [60][d]
5.1 *importance* of supporting traditional silviculture (bioenergy should support traditional silviculture) [62]
5.2 *permanency* of an organization (bioenergy organizations should be long-lasting, so as to support local culture) [62]
5.3 timeline (changes' impacts are dependent on the timeline; the longer the timeline, the greater the impacts) [62]
5.4 large, multi-national companies *do not support* local culture (large multi-national companies are not aware of local culture and are not prepared to adjust their practices to local culture) [62]
5.5 *positive effects* of export in terms of culture transfer (export of bioenergy is considered to be a positive culture transfer) [62]
5.6 *long tradition* of utilization of wood in heating (in Finland, there is a long tradition of using wood for heating, so wood-based bioenergy is culturally sustainable) [62]
5.7 *homogeneity* of practitioners (if the practitioners in the production chain have the same cultural background, conflicts are less likely) [62]
5.8 *new, efficient and comfortable* forestry machinery (bioenergy production requires new machinery, which is more comfortable to use) [62]
5.9 *importance* of securing culture of peat production (peat production has a long tradition in Finland, which should be supported) [62]

[a] In the original source defined as an indicators. In comparing the level of generality of indicator definition with the other 13 articles in the material of the study, the indicators are similar to criteria.
[b] In the original source defined as an verifiers. In comparing the level of generality of verifier definition with the other 13 articles in the material of the study, the verifiers are similar to indicators.
[c] In the original source defined as social indicator.
[d] In the original source defined as social criteria.

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